

Parton Distributions at Hadronization from Bulk Dense Matter Produced in Au+Au Collisions at $\sqrt{s_{NN}}=200$ GeV

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We present an analysis of Ω , Ξ , Λ and ϕ spectra from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV in terms of distributions of effective constituent quarks at hadronization. Consistency in quark ratios derived from various hadron spectra provides clear evidence for hadron formation dynamics as suggested by quark coalescence or recombination models. We argue that the constituent quark distribution reflects properties of the effective partonic degree of freedom at hadronization. Experimental data indicate that strange quarks have a transverse momentum distribution flatter than that of up/down quarks consistent with hydrodynamic expansion in partonic phase prior to hadronization. Our extracted parton transverse momentum distributions at the hadronization provide a unique constraint on the partonic evolution history. After the AMPT model is tuned to reproduce the strange and up/down quark distributions, the model can describe the measured spectra of hyperons and ϕ mesons very well where hadrons are formed through dynamical coalescence.

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Recent data from the Relativistic Heavy Ion Collider (RHIC) at BNL have demonstrated the formation of a hot and dense partonic matter in high-energy nuclear collisions at RHIC [1, 2, 3, 4]. Measurements of nuclear modification factor R_{CP} and elliptic flow v_2 for identified particles in the intermediate transverse momentum (p_T) region, $2 < p_T < 5$ GeV/c, exhibit a number of constituent quark (NCQ) scaling [5, 6, 7, 8, 9]. Such scaling can be explained by quark coalescence or recombination models [10, 11, 12], which provide an intriguing framework for hadronization of bulk partonic matter at RHIC. The essential degrees of freedom at the hadronization seem to be effective constituent quarks which have developed a collective elliptic flow during the partonic evolution. The elliptic flow v_2 of the constituent quarks at hadronization can be characterized by hadron $v_2(p_T)$ scaled by the NCQ, v_2/NCQ vs. p_T/NCQ [5, 6, 7, 9] and the hadron elliptic flow results from the sum of constituent quark collectivity. In this paper, we examine the constituent quark number scaling in transverse momentum spectra and use experimentally measured Ω , Ξ , Λ and ϕ p_T spectra to explore their connections to possible quark distributions at hadronization.

We focus our analysis on Ω , Ξ and ϕ spectra in contrast to previous coalescence or recombination model calculations, e.g. [10, 11], where pion and kaon spectra have been used to obtain the thermal parton component. The final state spectra of common hadrons like pion, kaon and protons in nucleus-nucleus collisions represent cumulative contributions from partonic dynamics, hadronization and kinetic evolution in hadronic stage. Collective radial flow can significantly alter the hadron p_T distribution and ordinary hadrons may decouple from the hadronic evolution at a very late stage depending on the hadronic interaction cross sections [13, 14]. Multi-strange hadrons, ϕ s, Ξ s and Ω s, are predicted to have a relatively small hadronic interaction cross section [14, 15]. These

hadrons carry the information of partons directly from the hadronization stage with little or no distortion due to hadronic evolution. In addition, there is no decay feed-down contributions to the Ω and ϕ spectra while for ordinary pion, kaon and protons the majority of the observed yield comes from decay production of resonance and weak decay states. Multi-strange hadrons offer unique advantages to probe properties of the partonic degrees of freedom at hadronization.

Quark coalescence or recombination models have been used extensively in explaining RHIC data recently [10, 11, 12]. There are some common features in the intermediate p_T region below 5 GeV/c in these models: i) baryons with transverse momentum p_T are mainly formed from quarks with transverse momenta $\sim p_T/3$, whereas mesons at p_T are mainly produced from partons with transverse momenta $\sim p_T/2$. ii) The production probability for a baryon or meson is proportional to the product of local parton densities for the constituent quarks. We argued that the $\Omega(p_T/3)/\phi(p_T/2)$ ratio can reflect the strange quark distribution prior to hadronization as the Ω baryon consists of three valence strange quark (sss) while the ϕ meson carries hidden strangeness ($s\bar{s}$). The $\Xi(p_T/3)/\phi(p_T/2)$ ratio will reflect the light quark information since the Ξ baryon consists of one light valence quark plus two strange quarks. We have assumed that the strange and anti-strange quark distributions are the same and the particle formation dynamics are dominated by coalescence or recombination of bulk partons. Our approach is consistent with the recombination model calculation by Hwa and Yang [10] using δ -function approximation for recombination and is valid in the intermediate p_T region up to 5 GeV/c for baryons and 4 GeV/c for mesons. Our approach allows us to extract properties of partons at hadronization directly from recent statistically improved measurements of multi-strangeness hadrons at RHIC [8, 9]. The valid-

ity of our approach can also be tested by experimentally examining parton distributions derived from independent ratios of various hadrons. The extracted parton p_T distribution provides unique constraints on partonic evolution history up to the hadronization epoch.

FIG. 1: (color online) Left panel: The derived quark p_T distributions in Au+Au collisions at RHIC. Gray bands are fittings with hydrodynamics inspired model (see text for details). Hatched area is the scaled range for the ϕ meson $dN/d(p_T/2)$ divided by the extracted strange quark dN/dp_{Ts} distributions. Right panel: similar as left panel but plotted as KE_T scale.

Fig. 1 presents the ratios of $\frac{\Omega+\Xi}{\phi}(p_T/3)$ and $\frac{\Xi^-}{\phi}(p_T/3)$ as a function of p_T/n_q , where n_q is the number of constituent quarks. The data points are from STAR measurements for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and the ratios are calculated at the quark-number scaled p_T . The shape of these ratios represent the strange and down quark p_T distributions. Within the statistical and systematic uncertainties there is no significant variation in the quark p_T distributions at hadronization for collision centralities from 0-5% to 40-60%. The collision geometry factor is cancelled out in these ratios. The feed-down contribution from higher state resonance $\Xi(1530)$ hasn't been included yet and will be discussed in detail in the following.

In order to characterize the quark p_T distribution, hydrodynamics motivated functions [16] have been used to fit the derived quark distributions, permitting extraction of model parameters characterizing the bulk freeze-out temperature (T_{th}) and collective radial flow velocities (v_T). For practical propose, we follow Fries's model [11], assuming v_T to be independent of source radii and azimuth angle with the radial expansion velocity profile as assumed in other models [16]. Fittings to the ratios derived from hadrons at different centralities simultane-

ously yielded $v_T = (0.54 \pm 0.13)c$ and $T_{th} = (131 \pm 48)$ MeV for strange quarks with $\chi^2/ndf = 10.7/12$, and $v_T = (0.36 \pm 0.19)c$ and $T_{th} = (170 \pm 40)$ MeV for light quarks with $\chi^2/ndf = 28.1/41$. If we fixed the parameter $T_{th} = 170$ MeV, we obtained $v_T = (0.43 \pm 0.03)c$ with $\chi^2/ndf = 11/12$ for strange quarks and $v_T = (0.36 \pm 0.02)c$ with $\chi^2/ndf = 26.6/41$ for light quarks. Varying the freeze-out temperature T_{th} to 160 (180) MeV, v_T values increased (decreased) $\sim 10\%$ for both strange and light quarks. These results are consistent with the picture that strange quarks may undergo a stronger hydrodynamical expansion in partonic phase than light quarks due to the larger effective quark mass; e.g., in Fries' model calculation the assumed quark masses are 460 MeV for s quarks and 260 MeV for u/d quarks [11]. A recent proposed transverse kinetic energy scaling [17], $KE_T = m_T - m_0$, has been applied in this analysis as well (m_T is the hadron transverse mass while m_0 is the rest mass). The consistency in the KE_T scaling, as shown in right panel of Fig. 1, provides further indication for coalescence or recombination of quarks where these quarks must have undergone a partonic evolution possibly described by hydrodynamics.

The physical picture to relate the particles ratios to strange and up/down quark distributions can be further tested with independent hadron ratios. In this picture ratios of $\Omega(p_T/3)/\Xi(p_T/3)$ and $\Xi(p_T/3)/\Lambda(p_T/3)$ should have a similar shape since both represent the ratio of s/d quark distributions. Fig. 2 shows the s/d ratios extracted from the Ω , Ξ^- and Λ spectra from central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, where the hadron p_T has been scaled by the NCQ. The raw $\Omega(p_T/3)/\Xi(p_T/3)$ and $\Xi(p_T/3)/\Lambda(p_T/3)$ ratios have a similar p_T/n_q shape indicating the validity of our approach. Recombination model calculation by Fries et al. [11] predicted a consistent shape between s/d quark ratio and the $\Omega(p_T/3)/\Xi(p_T/3)$ or $\Xi(p_T/3)/\Lambda(p_T/3)$ ratio after removing the different spin degeneracy factor. The calculated s/d ratio as a function of quark p_T deviates somewhat in shape from our parameterized curve based on experimental data. The overall agreement is reasonably well because of large experimental uncertainties involved. There is a normalization offset, presumably due to the fact that the model calculation does not include all resonance decay contributions.

Attempt to correct for feed-down contributions resulted to large statistical errors. The Ξ^- spectrum was corrected for feed-down from higher state resonance decays based on the measured $\Xi^0(1530)$ spectrum [18]. The contribution to the Ξ^- spectrum from $\Xi^0(1530)$ decays was $46\% \pm 14\%$, while the feed-down contribution from Ω decays was negligible. The Λ spectrum has already been corrected for Ξ and Ω weak decays, while the Σ contribution has not been subtracted [8]. This is shown as red circles in Fig. 2. The $\Xi(p_T/3)/\Lambda(p_T/3)$ ratio is about a factor of 3 smaller than the $\Omega(p_T/3)/\Xi(p_T/3)$ ratio. The feed-down contribution from Σ is significant. The contribution to the Λ spectrum from $\Sigma(1380)$ decays was $26\% \pm 5.9\%$ [19]. The Σ^0 production has not been measured

FIG. 2: (color online) Up panel: The s/d ratio derived from Ω , Ξ^- and Λ spectra in central Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV. Red circles represent the s/d ratio without Σ decays correction while gray hatched region is the corresponding ratio range after taking into Σ decays correction. The blue boxes represent the uncertainty in $\Xi(1530)$ feed-down estimation. Theoretical predictions (see text for details) have also been plotted for comparison. Low panel: similar as up panel but plotted with KE_T scale.

well experimentally at RHIC. Using thermal model parameters fit from central 200 GeV Au+Au data [20], the THERMUS thermal model gave a primordial Σ^0/Λ ratio of 0.67 and a final ratio of Σ^0 to inclusive Λ to be 0.36 [21]. On the other hand, string fragmentation model predicted a primordial ratio of 1/3 [22]. Assuming the Σ^0 feed-down is p_T independent, its contribution to the Λ spectra was assumed to be 25% – 36%. The $\Xi(p_T/3)/\Lambda(p_T/3)$ ratio after taking into account the Σ decay contribution is consistent with the $\Omega(p_T/3)/\Xi(p_T/3)$ data [cf. Fig. 2].

The large uncertainty due to the feed-down contributions will mostly change the normalization scale without significantly altering the shape of the spectrum involved in our ratio calculation. The similarity in the ratios of $\Omega(p_T/3)/\Xi(p_T/3)$ and $\Xi(p_T/3)/\Lambda(p_T/3)$ supports our picture that one can derive quarks distributions at the moment of hadronization from these multi-strange hadrons. Another independent check is to use the strange quark distribution from Ω to ϕ ratios, and derive the anti-strange quark distribution from ϕ meson data divided by

the strange quark distribution. The gray hatched area in Fig. 1 shows the anti-strange quark distribution, which is consistent with the strange quark distribution.

The consistency in s/d ratios derived from different hadron species provides clear evidence for hadron formation dynamics as suggested by quark coalescence or recombination models. The s/d ratios derived from the $\Omega(p_T/3)/\Xi(p_T/3)$ and $\Xi(p_T/3)/\Lambda(p_T/3)$ data both increase with p_T for $(p_T/3) < 1.0$ GeV/c, and approach saturation for $(p_T/3) > 1.0$ GeV/c. This p_T dependence may indicate that strange quarks have developed a collective flow stronger than that of light quarks by the time of hadronization [13, 14]. Comparison with Fries's model calculation and fit parameters extracted in Fig. 1 are consistent with stronger radial flow for strange quarks. The similarity of the s and d quark KE_T distributions [cf. bottom panel of Fig. 2]) may indicate a hydrodynamic behavior during the partonic evolution as suggested by Ref. [17]. But the exact nature of KE_T at the parton level is yet to be determined.

Theoretical models for hadron production in nucleus-nucleus collisions at RHIC typically involve initial conditions arising from parton scatterings, partonic evolutions, hadronization and hadronic evolutions. Different theoretical paradigms separate partonic from hadronic processes. Theoretical uncertainties due to hadronization scheme and hadronic evolution are major issues for quantitative description of properties of the QCD medium created at RHIC. Hydrodynamic calculations, for example [23], often employs Cooper-Frye [24] hadronization scheme. Fragmentation models or coalescence formation models may also be used which lead to different final state hadron momentum distribution and azimuthal angular anisotropy. The hadronic evolution processes have been added to hydrodynamic models as an afterburner and have been shown to significantly alter the spectra shapes of ordinary hadrons [25]. By using effective constituent quark degrees of freedom and their p_T spectra, it is hoped that major uncertainties from hadronization and hadronic evolutions may be avoided in model calculations. We will use a multiphase transport (AMPT) model [26] to illustrate that our derived strange and up/down quark distributions, representing a cumulative effect from initial conditions through partonic evolution, play an important role in determining the final state hadron momentum distribution. Details of the AMPT model can be found in Ref. [26] and won't be elaborated here.

The AMPT model has been used extensively to explain the RHIC data; e.g., by using parton scattering cross sections of 6-10 mb, the AMPT model with string melting scenario was able to reproduce both the centrality and transverse momentum (below 2 GeV/c) dependence of the elliptic flow and pion interferometry measured in Au+Au collisions at $\sqrt{s_{NN}}=130$ GeV at RHIC [27, 28]. It can reproduce the measured p_T dependence of both v_2 and v_4 of mid-rapidity charged hadrons and v_2 for ϕ -meson in the same collisions at $\sqrt{s_{NN}}=200$ GeV as

FIG. 3: (color online) The AMPT model calculation compared with the data in central Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV. The data have been scaled by factors for clarity.

well [29, 30]. Furthermore, it can produce a conic emission pattern through partonic cascading in central Au+Au collisions at RHIC [31]. These successes probably reflect the fact that the AMPT model has the ingredients for general features of partonic space-time evolution in these collisions. However, the model failed to reproduce the hadron transverse momentum spectra at RHIC as shown of dashed lines in Fig. 3. This may be due to the fact that partons in the AMPT model have not undergone the initial partonic evolution stage where partons would have developed a large radial flow. We remedy this deficiency in the model by modifying the original quark distributions before the partonic evolution at the moment of HIJING [32] interaction ceased. We effectively introduced an initial transverse momentum distribution to partons from HIJING string melting in the AMPT scheme, and let these partons follow the partonic evolution as described by Zhang's Parton Cascade (ZPC) model [33]. We tune the initial parton transverse momentum distribution so that after the ZPC evolution the parton distributions match our extracted strange and up/down quark distributions. The coalescence hadronization scheme in the AMPT model has been used for hadron formation. We refer to Ref. [34] for the details of partonic evolution history in the AMPT model.

The introduction of the initial parton transverse momentum distribution may be considered as an effective way to include early non-equilibrium partonic cascade

effect, not modelled by the string formation and melting scheme. It is also possible that this is an indication of insufficient parton cascading cross sections in the ZPC model [33] where only pQCD processes have been included. It is important to note that in our empirical approach the strange quarks seem to develop a harder p_T distribution than up/down quarks during the parton evolution. This may require to take into account the effective strange quark mass in the evolution process.

Fig. 3 shows results from the modified AMPT model calculation for hyperons and ϕ mesons. Our new AMPT calculation can reproduce the measured p_T spectra for multi-strange hadrons at mid-rapidity very well. We note that the hadronization process in the AMPT model is based on the coordinate space information (i.e., two nearest quark and antiquark are combined into mesons and three quarks or antiquarks are combined into baryons or antibaryons that are closest to the invariant masses of these parton combinations). In the coalescence scheme used by the AMPT model the partons must be close in coordinate space and there could be a broad range for momentum difference between coalescing partons. This is somewhat different from the ones by other groups [10, 11, 12] where partons are coalescing in momentum space, based on which we have obtained our parton transverse momentum distributions empirically. The consistency between our new AMPT calculation and the data indicates that an essential ingredient is the distribution functions of effective constituent quarks which readily turn into hadrons in coalescence or recombination calculations. Our extracted strange and up/down quark distributions provide an unique constraint on the partonic evolution history. Theoretical calculations of partonic cascading can be compared with our quark distributions without involving complicated hadronization and hadronic rescattering processes.

In summary, we have presented constraints on transverse momentum distributions for the effective constituent quarks at hadronization of the bulk partonic matter produced at RHIC. Our results suggest that strange quarks may have developed a collective radial flow stronger than that of light quarks during the initial partonic evolution. The coalescence model as implemented in the AMPT model can faithfully reproduce the measured multi-strange hadron transverse momentum spectra at RHIC when our derived quark distributions are used at hadronization of the partonic matter. The validity of our approach to explore quark transverse momentum distributions at hadronization has also been tested with independent particle ratios. Our approach in complement with the constituent quark number scaling in elliptic flow provides a means to measure quantitative quark properties at hadronization of bulk partonic matter.

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